Lessons learned for the Breeding Blanket designers from the design development of the European Test Blanket Module Systems

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26th IAEA Fusion Energy Conference, 17-22nd October 2016, Kyoto, Japan
Goals/Content of the talk

1. To recall the basic features of the main Breeding Blanket Concepts for DEMO; to recall the scope of the TBM Project; to summarize the main features of the European TBS Design

First part of the presentation: Breeding Blanket / ITER TBM Project

2. To discuss design issues/solutions encountered along the conceptual design of the European TBS that can be already brought to the attention of the DEMO breeding blanket designers

Second part of the presentation: Lessons Learned for DEMO Breeding Blanket development
**Breeding Blanket / ITER TBM Project**

**Functions of the Breeding Blanket**

A. **Tritium breeding to achieve the tritium self-sufficiency**

B. **Nuclear to thermal power conversion and heat extraction**

C. **Neutron/γ-ray shielding**

**Function A**

Breeding blanket materials are heated-up because:

a) Heat flux from plasma

b) Nuclear heat generated by neutrons slowing-down and nuclear reactions with Li.

The thermal power is then extracted by a suitable coolant and converted into electrical power through a conventional turbine-alternator group.

**Function B**

Neutron flux radially has to decrease of at least 1 order of magnitude to protect VV and magnets.

**Function C**

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Any Breeding Blanket (BB) consists of:

- Li bearing breeding material
- neutron multiplier
- structural material
- coolant

Any acceptable combination has to be satisfactory with respect to:

- safety requirements
- performance requirements
  - tritium self sufficiency
  - net plant efficiency
## Breeding Blanket / ITER TBM Project

<table>
<thead>
<tr>
<th>Blanket type</th>
<th>WCLL</th>
<th>HCLL</th>
<th>HCCB</th>
<th>WCCB</th>
<th>LLCB</th>
<th>DCLL</th>
<th>Molten Salt</th>
<th>Li-V</th>
<th>Adv. HCCB</th>
<th>SCLL</th>
<th>Li Evap.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural material</td>
<td>RAfM</td>
<td>RAfM</td>
<td>RAfM</td>
<td>RAfM</td>
<td>RAfM</td>
<td>RAfM + ODS</td>
<td>Ferritic Steel</td>
<td>V alloy (+ insulation)</td>
<td>SiCf/SiC</td>
<td>SiCf/SiC</td>
<td>W alloy</td>
</tr>
<tr>
<td>Breeder</td>
<td>Pb-16Li (liquid)</td>
<td>Pb-16Li (Liquid)</td>
<td>Li₄SiO₄, Li₂TiO₃ (pebbles)</td>
<td>Li₂TiO₃ (pebbles)</td>
<td>Pb-16Li (liquid) + Li₂TiO₃ (pebbles)</td>
<td>Pb-16Li (liquid)</td>
<td>FLiBe (liquid)</td>
<td>Li (nat.)</td>
<td>Li₂TiO₃, Li₂O (pebbles)</td>
<td>Pb-16Li (liquid)</td>
<td>Li (nat.)</td>
</tr>
<tr>
<td>Neutron Multiplier</td>
<td>Be (pebbles)</td>
<td>Be (pebbles)</td>
<td>Be (pebbles)</td>
<td>Be (pebbles)</td>
<td>He (8 MPa) + Pb-16Li</td>
<td>He (8 MPa)</td>
<td>FLiBe (liquid)</td>
<td>Li (nat.)</td>
<td>He (10 MPa)</td>
<td>Pb-16Li</td>
<td>Li (nat.) evap.</td>
</tr>
<tr>
<td>Coolant</td>
<td>H₂O (15 MPa)</td>
<td>He (8 MPa)</td>
<td>He (8 MPa)</td>
<td>He (8 MPa)</td>
<td>He (8 MPa)</td>
<td>He (8 MPa)</td>
<td>He (8 MPa) + Pb-16Li</td>
<td>He (8 MPa)</td>
<td>He (10 MPa)</td>
<td>Pb-16Li</td>
<td>Li (nat.) evap.</td>
</tr>
<tr>
<td>T coolant</td>
<td>265 - 325</td>
<td>300 - 500</td>
<td>300 - 500</td>
<td>290 - 520</td>
<td>325 - 500</td>
<td>300 - 550</td>
<td>300 - 480 (He)</td>
<td>460 - 700 (PbLi)</td>
<td>330 - 610</td>
<td>600 - 900</td>
<td>765 - 1100</td>
</tr>
</tbody>
</table>

### Reactor concept studies

- PPCS-A
- PPCS-AB
- PPCS-B
- SSTR
- DEMO-S
- ARIES-ST
- APEX
- PPCS-C
- FFHR-2
- ARIES-RS
- DREAM
- A-SSTR2
- ARIES-AT
- TAURO
- APEX-EVOLVE

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Breeding Blanket / ITER TBM Project

TBM Program in ITER

3rd ITER Council (2008) established the TBM program in ITER

The TBM project provides test blankets to test and validate design concepts of tritium breeding blankets relevant to a power-producing reactor.

- through a test environment (Test Blanket Module) that reproduces the operating conditions foreseen in a DEMO Breeding Blanket
- through systems that adopts technologies that are relevant for a DEMO BB when compatible with ITER operational requirements
- through the development and validation of predictive modelling tools that are needed for the design of a DEMO BB
Breeding Blanket / ITER TBM Project

Helium-Cooled Pebble-Bed

~1.6 m

Helium-Cooled Ceramic Breeder

Helium-Cooled Ceramic Reflector

Water-Cooled Ceramic Breeder

Helium-Cooled Lead-Lithium

Lead-Lithium Ceramic-Breeder
Breeding Blanket System

**TES**: Tritium Extraction System  
**CPS**: Coolant Purification System  
**HCS**: Helium Cooling System

Fuel Cycle

**TEP**: Tokamak Exhaust Processing System  
**ISS**: Isotope Separation System  
**VDS**: Vent Detritiation System
As the conceptual design phase of the HCLL and HCPB-TBS has been concluded and we have entered the first stage of the preliminary design phase, there is already a significant RoX (Return on Experience) which can be delivered to the DEMO designers.

Here we’ll focus not on generic recommendations but on **four examples of specific technical points** that the Breeding Blanket designers can already “take on board”.

These four examples deal with:

1. Licensing Procedure and impact on the design
2. Design of the Instrumentation
3. Definition and implementation of the Safety Functions
4. A specific integration issue: the problem of the tritium contamination
Lessons learned: Licensing Process

- In order to get the license to operate, the Operator - ITER Organization - is requested, among many others commitments, prescriptions and demands from the regulator - to carry out a Nuclear Safety Demonstration (part of the Safety Demonstration) in which the risks originated from the ITER operation are identified together with the provisions to prevent or limit them.

- As per the French BNI order December 2012 these provisions are ensured by components identified as PIC (Protection Important Components). PIA (Protection Important Activities) are the processes of design, construction, installation and testing of PIC.

- As per the BNI order, PIC/PIA must be strictly identified, controlled and reported.
Lessons learned: Licensing Process

- Identification of “PIC” and “PIA”
- Identification of the “defined requirements” for PIC and PIA
- Propagation of the defined requirements through the supply chain
- Nuclear Safety Demonstration
- Nuclear Safety Analysis Methodology
- Nuclear Safety Analysis Implementation
- Verification of the implementation of the defined requirements in the design
- Compliance with French regulation: ESPN order 2005
- ESP/ESPN classification
- Safety Report (different versions)
### Lessons learned: Licensing Process

Licensing process and impact on the design

Safety/ESP/ESPN classification of the main components of the HCPB-TBS Coolant Purification System

<table>
<thead>
<tr>
<th>Equipment ID</th>
<th>Description</th>
<th>Type</th>
<th>Fluid</th>
<th>Safety Class</th>
<th>Quality Class</th>
<th>Normal operating temperature of fluid, °C</th>
<th>Maximum allowable temperature of fluid, °C</th>
<th>Design temperature of fluid, °C</th>
<th>Normal operating pressure, MPa</th>
<th>Maximum allowable pressure, Bar</th>
<th>Fluid/Group Fluid</th>
<th>Pressure category as defined in PE or NPE</th>
<th>Nuclear level as defined in NPE</th>
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</thead>
<tbody>
<tr>
<td>56A2HP-Fi-2001</td>
<td>Filter</td>
<td>Accessory</td>
<td>gas</td>
<td>SIC-2</td>
<td>QC1</td>
<td>90</td>
<td>450</td>
<td>90</td>
<td>8.1</td>
<td>101</td>
<td>Gas/Group 2</td>
<td>II</td>
<td>No NPE</td>
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<tr>
<td>56A2HP-Fi-2004</td>
<td></td>
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<td>56A2HP-KK-2001</td>
<td>Economizer</td>
<td>vessel</td>
<td>gas</td>
<td>SIC-2</td>
<td>QC1</td>
<td>90-250</td>
<td>500</td>
<td>500</td>
<td>8.1</td>
<td>101</td>
<td>Gas/Group 2</td>
<td>II</td>
<td>No NPE</td>
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<td></td>
<td>120-280</td>
<td>500</td>
<td>500</td>
<td>8.1</td>
<td>101</td>
<td>Gas/Group 2</td>
<td>II</td>
<td>No NPE</td>
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<tr>
<td>56A2HP-KK-2002</td>
<td>Cooler</td>
<td>vessel</td>
<td>liquid</td>
<td>SIC-2</td>
<td>QC1</td>
<td>10</td>
<td>10</td>
<td>30-40</td>
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<td>101</td>
<td>Liquid group 2</td>
<td>II</td>
<td>No NPE</td>
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<tr>
<td>56A2HP-KK-2004</td>
<td>Economizer</td>
<td>vessel</td>
<td>gas</td>
<td>SIC-2</td>
<td>QC1</td>
<td>35-155</td>
<td>500</td>
<td>500</td>
<td>8</td>
<td>101</td>
<td>Gas/Group 2</td>
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<td>56A2HP-HT-2004</td>
<td>Heater</td>
<td>vessel</td>
<td>gas</td>
<td>SIC-2</td>
<td>QC1</td>
<td>155-400</td>
<td>500</td>
<td>500</td>
<td>8</td>
<td>101</td>
<td>Gas/Group 2</td>
<td>II</td>
<td>No NPE</td>
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<td>56A2HP-TA-2003</td>
<td>Heated (impurity) getters</td>
<td>vessel</td>
<td>gas</td>
<td>SIC-2</td>
<td>QC1</td>
<td>400</td>
<td>500</td>
<td>500</td>
<td>7.9</td>
<td>101</td>
<td>Gas/Group 2</td>
<td>IV</td>
<td>No NPE</td>
</tr>
</tbody>
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1. **To identify PIC/PIA and related defined requirements** already in the conceptual design, securing their propagation into the supplier chain.

2. **To carry out at early stage of the design the ESP/ESPN classification** of the main components as this impacts the both design and manufacturing requirements. A reliable classification requires much effort. A close collaboration with a Notified Body is strongly recommended not only for the classification but for the general understanding of the ESP/ESPN constraints and requirements (*conformity assessment, essential safety requirements*).

3. **To obtain relevant experimental data for the validation of the safety codes** in a wide application domain that covers both fusion related phenomena and specific plant parameter range. *Example of this is the recent experimental activity carried out at ENEA (Italy) to simulate an In-TBM LOCA and subsequent correlation of the results with RELAP 5.*
TBS instrumentation must perform reliably in the ITER challenging environmental conditions. Depending on the sub-system, the number of physical parameters and range of measurement in the TBM set and ancillary systems is vast.

- temperature, 300‡900 °C, for TBM structural and functional materials and ancillary system process fluids
- mass flow-rate of the process fluids, from few NI/s to some thousand NI/s
- pressure of the process fluids, from ambient pressure up to 8 MPa
- magnetic field, up to 5 Tesla in the TBM location
- electrical current, up to several thousand A for the eddy currents
- neutron flux, up to $10^{18}$ n/m$^2$/s in the TBM
- neutron spectrum, from eV to MeV
- gamma radiation field, from $10^{-5}$ to some Sv/h
- displacement/position, from $10^{-3}$ to some mm
- tritium concentration/partial pressure, from $10^{-2}$ to $10^{2}$ Pa, in the process fluids

Lessons learned: Instrumentation Design

- Permeation based sensors
- Temperature and strain measurement with distributed fiber optic arrays (regenerated FGB sensors)
Main challenges on instrumentation:

- **Radiation Field**, both direct from plasma and secondary emission from activated materials
- **Magnetic Field** effects

Both fields can cause drift in the sensor signals and degradation of accuracy, with impact on the machine availability.

Following the ITER recommendation, sensors and related instrumentation chain have been categorized in three tiers, depending on their functions:

- **safety**
- **investment protection**
- **conventional control**

Depending on the tier to which they belong, different requirements in terms of accuracy, reliability, quality assurance, resistance to radiation, must be considered.
Lessons learned: Instrumentation Design

Recommendations

a. To categorize at an early stage the instrumentation among the three tiers as this will allow to better identify the proper design requirements

b. To prepare soon accurate P&ID in order to have a full control of the instrumentation to be deployed in the different breeding blankets systems

c. To implement appropriate shielding provision on the electronics to avoid performance degradation due to radiation and magnetic field

d. To select sensors assuring high performance while reducing integration problems in case of limited space: example is the possible use of optical fibers instead of thermocouples in the breeding blanket modules
Lessons learned: Safety Functions

Three typologies of safety functions have been identified specifically for HCLL and HCPB-TBS:

1. **isolation of TBS sub-systems** to ensure radioactive inventory confinement
2. **pressure release** in case of over-pressurization of the TBS sub-systems
3. **Plasma Shutdown (FPS)** requested by the TBS Plant Safety System to the Central Safety System

They are triggered upon detection of abnormal conditions by PIC instrumentation deployed in the different TBS sub-systems.

<table>
<thead>
<tr>
<th>Accident Scenario</th>
<th>Primary parameter(s) detected</th>
<th>Implemented HCLL-Safety Functions or single actions</th>
<th>FPS triggered by CSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex-vessel LOCA</td>
<td>Pressure decrease in HCS</td>
<td>HCS circuit isolation</td>
<td>YES</td>
</tr>
<tr>
<td>In-TBM LOCA</td>
<td>Pressure increase in Pb-Li loop</td>
<td>- HCS circuit isolation function - Pb-Li circuit depressurization</td>
<td>YES</td>
</tr>
<tr>
<td>In-vessel LOCA</td>
<td>- Pressure decrease in HCS - Different in/out He flow-rate across TBM</td>
<td>-HCS circuit isolation -PbLi circuit isolation</td>
<td>YES</td>
</tr>
<tr>
<td>LOFA in HCS</td>
<td>- Low He mass flow-rate in HCS - Low current absorbed by He circulator</td>
<td>HCS circuit isolation (if FPS is triggered)</td>
<td>YES</td>
</tr>
<tr>
<td>LOHS</td>
<td>Temperature difference increase across the HCS heat sink (heat exchanger)</td>
<td>no functions/actions if FPS is triggered</td>
<td>YES</td>
</tr>
<tr>
<td>Pb-Li loop pipe break</td>
<td>Pressure decrease in Pb-Li loop</td>
<td>Pb-Li circuit isolation</td>
<td>NO</td>
</tr>
<tr>
<td>TRS pipe break</td>
<td>Pressure decrease in TRS loop</td>
<td>TRS circuit isolation</td>
<td>NO</td>
</tr>
<tr>
<td>CPS pipe break</td>
<td>Pressure decrease in CPS loop</td>
<td>CPS circuit isolation</td>
<td>NO</td>
</tr>
<tr>
<td>HCS-PCS failure</td>
<td>Pressure increase in HCS</td>
<td>HCS circuit depressurization</td>
<td>YES</td>
</tr>
</tbody>
</table>
Lessons learned: Safety Functions

1. **Design of the Safety Functions against the single failure criterion**, implementing the principle of defense-in-depth, **requires the redundancy of safety devices**, sensors, actuators and I&C cubicles

2. **Use of 2oo3 logic** for sensors triggering the safety functions is highly recommendable to avoid that spurious signals may lead to unjustified shutdown of ITER

*This architecture has been implemented in the current design of the HCLL and HCPB-TBS.* As an example, six pressure sensors, distributed in pair in three different locations, will trigger the closure of the HCS isolation valves in case of an ex-vessel LOCA.

Taking into account that this approach is applied to all TBS sub-systems and to all PIC sensors, there will be a proliferation of sensors and cables in the Port Cell, with integration issues and lack of space.
Recommendations

1. The identification of the Safety Functions and their implementation have to be considered early in the design. This implementation must be detailed, including the selection of the safety devices with the appropriate performance features.

2. Using for the investment protection the same instrumentation adopted for the safety functions is a design solution for the two European TBS implementing a signal duplicator, located in the Plant Safety System (PSS) cubicle. This allows reducing the number of sensors, then lowering design effort, cost and integration issues.
Lessons learned: Integration

Example of Integration Issue: tritium contamination in the areas hosting the TBM systems

- Difficulty to respect the authorized level of tritium concentration in the Port Cell #16 (maximum 1 DAC during operation/maintenance; 1 DAC due to tritium contamination: $3.4 \times 10^5$ Bq/m$^3$), where many components of HCLL and HCPB-TBS sub-systems are located
- This is mainly due to the high tritium permeation rate from these TBS components into the Port Cell, combined with low DS capacity
- Tritium absorbed in the epoxy painted walls is slowly released, challenging the possibility of having hands-on maintenance in the Port Cell

Generic Port Cell in ITER

Tritium concentration in the Port Cell#16 during operation and short term maintenance (curve by TMAP4)
Lessons learned: Integration

Example of Integration Issue: tritium contamination in the areas hosting the TBM systems

Recommendations

1. to implement in the design provisions to strongly reduce the tritium permeated into the areas hosting the breeding blanket systems. For the Breeding Blankets based on Pb-16Li, they are:
   - design of a tritium extractor from Pb-16Li with high extraction efficiency (>80%) to lower the tritium partial pressure in the liquid metal, then reducing the tritium permeation rate into the plant areas
   - use of tritium permeation barriers on the inner walls of the piping
   - adoption of suitable operating conditions: i) PbLi flow-rate as high as possible to reduce the tritium partial pressure in Pb-16Li; high CPS flow-rate to keep low the tritium partial pressure in the main cooling system

2. to increase the DS recirculation rate, as the steady state tritium concentration in the air is inversely proportional to the DS flow-rate for a given tritium source rate

3. to focus on suitable liners to protect the concrete walls, ensuring a fast release of HT/HTO during the maintenance phase
The conceptual design of HCLL and HCPB-TBM systems has been concluded and the first part of the preliminary design phase in now approached. The technologies adopted in the different systems to fulfill the requested functions and top level design requirements have been selected. The main components have been sized and preliminary integration in the relevant ITER buildings implemented. Preliminary set of design and safety requirements have been identified.

Contribution from TBM system design to the DEMO BB design is already relevant in terms of RoX.

There are examples of outcomes from the design of HCLL and HCPB-TBS than can be already taken in account by the designers of a breeding blanket for DEMO. Four of them have been considered here. They deal with:

- Licensing Procedure and impact on the design
- Design of the Instrumentation
- Definition and Implementation of the Safety Functions
- A specific integration issue: the problem of the tritium contamination

The general recommendation from these examples is to consider the related specific provisions, based on the outcomes of the TBM Project activities, already at the conceptual phase of the Breeding Blanket Design.
Thank you for your attention

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